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The goal of the program was the further define the material factors controlling the susceptibility of steels to adiabatic shear strain localization. A variety of steels were impacted with projectiles having a flat-bottomed cylindrical step on the impacting end. The materials examined included: Armco Iron, Ti-gettered high purity iron, AISI 1018, AISI 1040, 2¼ Cr-1 Mo chemical reactor steel, a dual phase steel, H26 Tool steel, Hadfield's austenitic manganese steel, 304 and 310 stainless steels.

INVESTIGATION OF THE MATERIAL FACTORS IN THE ADIABATIC SHEARING OF STEELS

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esadiaberences in such properties as thermal conductivity and diffusivity can be neglected because of the short time available for heat flow during deformation, then two properties, rate of thermal softening and rate of strain hardening, remain as the two most significant factors in the tendency to adiabatic shear localization. The former should promote shear localization whereas a high rate of strain hardening should reduce the susceptibility. A number of different materials were examined in this program for their susceptibility to strain localization during impact with these factors the major consideration.

Although not initially planned, the impact process and the mechanics of target penetration came to be recognized as having a very strong influence on the results of this study of shear band formation; hence, a portion of the program was spent trying to gain a better understanding of the roles of such factors as target thickness and support structure on the observed shear banding.

The steels studied included the following. Armco Iron, Ti-gettered high purity iron, AISI 1018, AISI 1040, 2¼ Cr-1 Mo chemical reactor steel, a dual phase steel, H26 tool steel, Hadfield's austenitic manganese steel, 304 stainless steel and 310 stainless steel. The behavior of 70-30 brass and a titanium alloy were studied as non-ferrous metals for comparison with the ferrous metals in their response to dynamic deformation.

Of all the materials studied, only the Armco Iron, the Ti-gettered iron and the annealed 70-30 brass targets did not fail in some way when subjected to impact by stepped projectiles. These materials deformed extensively with extensive bulging of the distal side of the target.

Although they did not fail under the conditions imposed by the current experiments, they never the less would undoubtedly show poor resistance to higher velocity impact. The H26 tool steel was studied in the mill annealed condition and also after a long time spheroidization heat treatment. This particular tool steel was selected for study because of its resistance to thermal softening. Unfortunately, even when in the highly spheroidized condition, the toughness of this tool steel was so low that the target fractured in a brittle manner with no shear band formation. Of the other ferrous metals studied, only quenched and tempered AISI 1040 steel and highly cold worked AISI 1018 produced transformed shear bands on impact. In all the other steels, there was significant shear strain localization followed by ductile shear fracture and "plugging" when large step heights and higher impact velocities were employed. It thus appears that a high rate of strain hardening in target alloys, such as exhibited by the Hadfield steel and stainless steels, is not alone sufficient to protect against target failure.

It was also shown that cold-worked target materials are much more susceptible to target plugging than their weaker annealed counterparts. From a theoretical viewpoint, for a given strain increment, $\delta\epsilon$, the heat generated is proportional to the flow stress, i.e., the heat generated is proportional to the work done, $\sigma\delta\epsilon$. In addition, the strain hardening capacity of highly cold worked metal is relatively low. Full hard 70-30 brass targets formed plugs rather easily while the annealed brass showed only general deformation. AISI 1018 targets were examined in three conditions: as-received (with moderate cold work), annealed, and annealed plus 67 percent cold reduction. In the first two conditions only diffuse deformed bands formed under all test conditions. At 330 fps transformed bands formed in the cold worked steel although at 302 fps only deformed bands were produced. These results show clearly the harmful effects of high strength level accompanied by low rates of work hardening, although, as stated earlier, high rates of work hardening did not per se guarantee freedom from thermoplastic strain localization.

The Hadfield steel was studied both in the as-received condition and after a long solutionizing treatment. In the as-received condition, the grain boundaries were covered with an extensive carbide network that results in brittle intergranular fracture under tensile stress. This carbide network is removed by a high temperature solutionizing treatment. The Hadfield steel targets were observed to behave substantially differently in the two different conditions of thermal treatment.

In the as-received condition, any possible tendency to form adiabatic shear bands was preempted by the ease of ductile shear fracture. Thus, instead of "propagating" shear bands extending from the projectile indentation, cracks of increasing length were formed. Examination of the fracture surfaces in the SEM showed that fracture took place during indentation and not during some elastic rebound phenomenon. Metallographic observations indicated extensive micro twinning accompanying the general deformation. This is presumably a major contributor to the high rate of work hardening.

In the solutionized steel, the tendency to fracture was considerably reduced. At a depth of penetration of 0.4 mm no band formed at any obtainable velocity, a depth of penetration of 0.65 mm being required for a shear band initiation. At higher velocities there was extensive band lengthening and fracture. These bands are relatively narrow and etched white against a dark back ground structure consisting of extensive deformation twinning even though the bands look, and are expected, to be of the deformed type. A considerable effort was expended in an attempt to obtain thin foils of the band structure for examination in the TEM. None were successfully obtained, however.

It also became clear during this program that a significant improvement in the accuracy of the projectile impact in relation to the target support system would lead to a substantial reduction in the scatter in the measurements of band lengths as off-center hits often produced bands of substantially different length on one side of the indentation compared with the band length on the other side. Sectioning the target parallel to the plane of target rather than perpendicular to it as is customary also revealed additional problems in measurement and interpretation of results. Although the projectile step is a perfect right circular cylinder, the shell of locally deformed material below this step is, for one reason or another, neither perfectly circular nor perfectly cylindrical. Thus, exactly what size shear bands are observed in the normal section is dependent on the specific indentation diameter chosen for the transverse section. Moreover, when plug formation begins, the non-linearity of the plug walls leads to the appearance in the transverse section of intermittant fractures separated by "shear bands". The latter, however, appear to be structures equivalent to shear bands but formed by the friction welding of the two sliding fracture surfaces when the local pressure during sliding becomes too intense as the imperfectly cylindrical plug is pushed through the surrounding target.

Attempts to study the effects of target thickness and consequent changes in the pattern of material flow and adiabatic shearing in the target during indentation by stepped projectiles were unsuccessful. For all but the softest targets, the tool steel projectiles fractured at the step periphery early during indentation, producing an odd-shaped indentation that could not be correlated with normal indentation behavior. Fracture of the projectile step was always associated with the intersection of the step with the body of the projectile which acted as a stress concentration. The angle of fracture was approximately 35° to the lateral surface of the cylindrical step, independent of the type of tool steel used for the projectile or the height of the step. This independence supports a non-material explanation for the fracture angle - that it results from a relatively high frictional stress on the lateral surface of the step during indentation. In any case, continual projectile failure precluded the study of target thickness and adiabatic shear band formation. In addition to examining a second tool steel as a potential projectile material, a 350 maraging steel was also tried. It did not, however, provide sufficient hardness to maintain a sharp edge at the step periphery during indentation.

Summary and Conclusions

Most materials will fail during impact by stepped projectiles, the exceptions being annealed high purity Ti-gettered iron, Armco iron, and

70-30 brass. The reason is simply that these materials distribute the strain through out a large portion of the target; they would not withstand significantly higher velocity impact without penetration, however.

Failure by ductile fracture followed by plug-formation occurs in a preponderance of the ferrous material examined while obvious evidence of thermally-assisted strain localization was only observed for solutionized Hadfield's steel, quenched and tempered AISI 1040, and highly cold-worked AISI 1018 steel. It appears that ductile shear fracture plays a greater role in target failure during indentation than has been thought heretofor.

Since both Hadfield's steel and 304 stainless steel have high rates of work hardening yet exhibit relatively easy shear band formation, a high rate of work hardening is obviously not sufficient to prevent adiabatic shear localization. Conversely it was shown that in the highly cold worked condition are quite susceptible to such strain localization.

The differences in strain localization behavior in the Hadfield steel as a function of heat treatment, the ease with which strain localized in materials with high rates of work hardening, combined with the relative ease of target failure by ductile shear failure suggest two areas that should be investigated further:

1. Role of material cleanliness on the dynamic failure process.
2. The role of microstructural stability in adiabatic strain localization during high velocity deformation.

Attempts to study the influence of target thickness on shear band generation using stepped projectiles were unsuccessful because of projectile fracture during indentation.

Finally, and most critical for any future experimental studies of this type, it was clearly demonstrated that the accuracy with which the projectile impacts the small targets relative to both the target center and the location of the target support system is a major factor in determining the degree of scatter in the observed shear band dimensions. This problem must be addressed in any future experimental study; a few preliminary experiments have indicated a potential solution to this problem.

LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD:

"Adiabatic Shearing - General Nature and Material Aspects", in Material Behavior under High Stress and Ultrahigh Loading Rates, J. Mescall and V. Weiss, Eds., Plenum Press, N.Y., 1983, p. 101.

"Adiabatic Strain Localization During Dynamic Deformation", in Deformation Processing and Structure, G. Krauss, Ed., ASM, Metals Park, Ohio, 1984.

"The Tendency Towards Adiabatic Shear in H26 High Speed Tool Steel, Armco iron, 1018 Steel and 1040 Steel Quenched and Tempered at 200°C and 400°C", M.S. Thesis, F.T. Zimone, Drexel University, June 1983.

"Response of Hadfield's Austenitic Manganese Steel to Projectile Impact" - In Preparation.

Scientific Personnel Supported on This Project

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Mr. F.T. Zimone, M.S. in Materials Engineering, June 1983.